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Energy Performance Evaluation and Development of Control Strategies for the Air-conditioning System of a Building at Construction Stage

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Abstract: Energy consumption of HVAC systems in commercial buildings takes a great part of the total building energy consumption. Energy performance evaluation plays an important role in building energy efficiency improvement for existing buildings and new buildings. It is also the basis for the retrofitting measure evaluation for existing buildings and the control improvement evaluation of new buildings for building energy performance contracts. In this study, the energy performance evaluation of a super high-rising commercial office building in construction is presented. Alternative control strategies are proposed to improve the energy efficiency based on the current measurements of the original design as well as additional metering instruments as requested. These control strategies mainly involve optimal chiller sequencing control, cooling tower sequencing control, optimal water pressure differential set-point control, AHU supply air static pressure reset control and DCV-based fresh air control, etc. To assess the economic feasibility, the benchmark electricity consumption and the optimal electricity consumption using alternative controls strategies are estimated using dynamic simulations. The results show that the electricity savings using the alternative control strategies can cover the costs of an additional metering system and related software and hardware in about one year.

Keywords: Energy performance evaluation, control strategy, benchmark, dynamic simulation

1. INTRODUCTION

The total energy consumption of buildings has increased dramatically over the last twenty years both in Chinese Mainland and in Hong Kong. Due to the extremely high fuel oil price and shortage of energy supply, the society and the building profession have paid much greater concern on building energy efficiency. The business sectors have also recognized that it is profitable business in offering building energy retrofitting and upgrading services. Building owners nowadays are much more concerned on improving the energy efficiency whether in existing buildings or new buildings in design or in construction.

For commissioning of existing buildings, building level energy diagnosis and evaluation play an important role in determining if building system operates normally or what causes the building system in abnormal state[1,2] as well as offering building energy retrofitting and upgrading alternatives[3,4]. For diagnosis and evaluation purposes, reference energy models are very important to accurately predict absolute performance data for performance benchmarking by comparing with these measurements. Many researchers have developed various reference models for applications viewing the building system as a whole. These models can be mainly categorized into physical models [5], data driven models [6,7] and gray models[8,9]. However, semi-physical models are more preferable alternatives for long term performance prediction using identified parameter with short-term performance measurements [10].

As far as the commissioning of the buildings in design or in construction is concerned, detailed simulations are important for building energy performance evaluation. The simulations are also the basis of investment budgets and cost evaluation of system operation and maintenance. Although there are many well-developed and successful commercial simulation software packages, such as EnergyPlus [11] and DOE-2 [5] etc., it is very difficult to complete building cooling load calculation, water system simulation, air system simulation etc. in one single simulation package. System configurations (such as water system and air system) in these simulation packages are quite complex and time-consuming or even frustrated although the above software packages provide these simulation functions. As for detailed dynamic simulation tests of various control strategies, these packages can provide limited help. Therefore, many researchers developed different simulation platform for specific usage [12,13,14].

In this study, one research project is presented. In this project, we are required to implement sophisticate control strategies and propose more energy efficient control strategies to saving more energy while maintaining the indoor environmental requirement on the basis of original design of a being constructed super high rising commercial office building. These strategies cover chiller system, water side systems and air-side systems etc. To apply the control strategies, some measurement instruments are needed to add into the original systems to allow more effective and efficient control. These measurements are integrated to the intended automatic temperature control system (ATC) and building management system (BMS). The software of control strategies and supervisory control and the corresponding hardware

are also needed to be connected or be parallel to the originally intended control platforms. These additions will result in a large amount of cost on the developer. Therefore, before implementation of control strategies beyond that in the original design, feasible technical and economic analysis is necessary. This study mainly presents the implementation architecture of control strategies, additional metering systems and simulations for the assessment of energy saving potential as well as the preliminary results. In the next section, the building and the major HVAC system are described.

2. BUILDING AND SYSTEM DESCRIPTIONS

2.1 Building description

Figure 1 is the schematic profile of the building for the research project. This building is super high-rising of 490 meter high above the ground with about 440,000 m^2, involving a basement of four floors, a block building of 6 floors and a tower building of 112 floors. The basement is mainly used for car parking with about 24,000 m^2. The block building from the ground floor to 5th floor mainly serves as commercial center involving restaurants, shopping markets and exhibition halls. The gross area is about 67,000 m^2. For the tower building, the 6th and 7th floors serve as mechanical floor (M1) to accommodate chillers, cooling towers, pumps etc. The 8th is refugee floor. From 9th to 98th floors, there are mainly commercial office floors with each floor of length 66 *m* and width 65 *m* except that the 41st and 77th floors are used as refugee floors, and the 42nd (M2), 78th (M3) and 99th (M4) floors are used as mechanical floors to accommodate mechanical equipments such as heat exchangers, pumps, PAU and fans etc. A six-star hotel is located from the 100th to 118th floors.

The whole building is being constructed primarily of reinforced steel concrete. The transportation systems and AHU plants are located in the core of each floor with a quasi-rectangle of 45 *m* by 41 *m*. The blocking building is being in construction. The first phase from basement to 41st floor (Phase I) will be put in use at the end of next year.

2.2 Zoning and system description

The building is divided into five zones considering the water pressure duration and human evacuation in case of a fire. The floors below 7th floor are Zone 1. Zone 2 involves the floors from the 8th to 41st floor. Zone 3 is from the 42nd to 77th floor and Zone 4 from the 78th to 98th floor. The hotel from the 100th floor to 118th floor is Zone 5. Considering the usage characteristics of the hotel, separate air-cooled chillers are designed to provide chilled water source for Zone 5, which are located at the floor M4. From Zone 1 to Zone 4, the chilled water sources are provided by water-cooled chillers on the floor M1.

Fig. 1 Profile of International Commerce Center

The design total cooling load of the building except the six-star hotel is 43000 *kW*, equal to about 125 W/m^2 (not including the basement). Six centrifugal chillers of high voltage (10,000 *V*) with the capacity of each one 7230 *kW* are designed to supply the chiller water at 5.5 ℃. The chiller scheme is proposed in view of the higher efficiency and less spatial requirement, especially on the space saving for the associated switchrooms and transformer rooms. The schematics of the chiller system and water system are described in Figure 2. The nominal power consumption of each chiller is 1346 *kW* at the full load condition. The heat generated by the chiller motors are taken away mostly by the refrigerant. Heat dissipated from the chillers is rejected by means of evaporate water cooling towers, total eleven units with total capacity 52,000 *kW*.

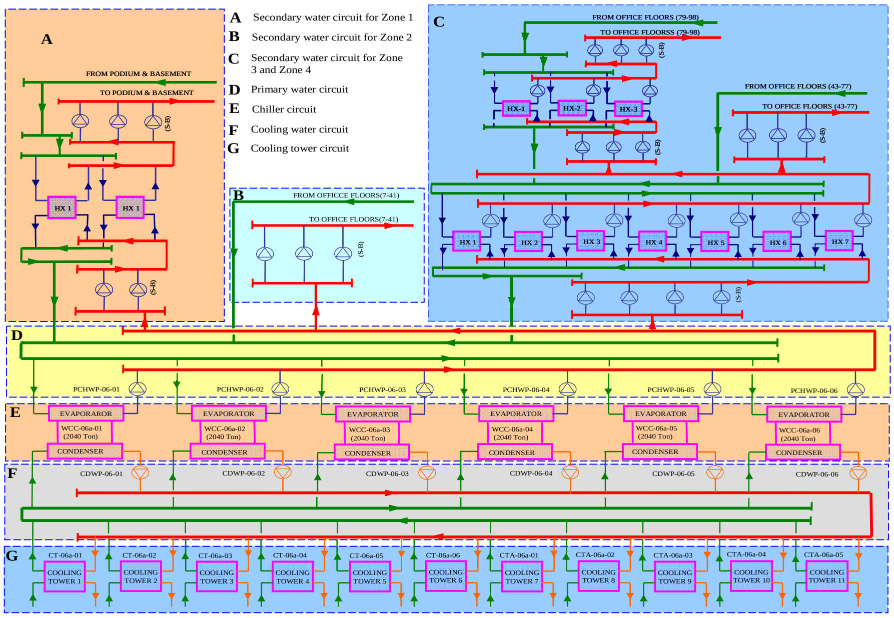

Fig. 2 Central chiller system and water system

The water system involves zones from Zone 1 to Zone 4. The designed water working pressure of Zone 1 is 16 *Bar*. The other three zones are 20 *Bar* respectively. Therefore, Zone 2 (indicated as B) is supplied with secondary chilled water directly. The cooling load of Zone 2 is about 30% of the total cooling load. To avoid the high water static pressure from other zones, Zone 1 (indicated as A) is supplied with secondary water through heat exchangers while the secondary chilled water just after chillers as cooling source. The heat exchangers are located on M1 floor. The design outlet and inlet temperatures of the heat exchangers are 6.3 ℃ and 11.3 ℃ respectively. The cooling load of this zone is 19% of the total cooling load.

Zone 3 and 4 are supplied with the secondary water through the heat exchangers (named as the 1st heat exchangers) located on M2 floor (indicated as C in the above figure). The design inlet and outlet temperatures of the 1st heat exchangers are 11.3 ℃ and 6.3 ℃ respectively. One part of the primary secondary chiller water after the 1st heat exchangers is delivered to Zone 3 by the secondary water pumps located on the same floor. Another part of the water is delivered to M3 floor for the heat exchangers (as the 2nd heat exchangers) by the secondary water pumps also located on M2 floor. The design outlet and inlet chilled water temperatures are 7.1 ℃ and 12.1 ℃ respectively. The water systems after the 2nd heat exchangers are the conventional primary-secondary water systems. All the pumps are equipped with *VSD*s to allow energy efficiency except that the primary water pumps directly connected to chillers are constant speed allowing more stable working conditions for chillers.

Most of the air-handling terminals are AHUs except that some fan coil units are used in the block building. For each tower building floor, two AHU located in the core is used to handle the mixture of the recycled air from office and fresh air. All the handled air from the outlets of both two AHU units is delivered to two ring supply air ducts with rectangle section. The application of ring duct systems at each floor can improve system reliability and facilitate future maintenance and operation. All the supply air is finally delivered to office space through about one hundred VAV boxes of each design maximum flow rate at about 0.25m^3/s. All the return air is brought to the plenum above the ceiling through louvers and then meet at the main return air ducts, which are connected AHUs directly. The fresh air is delivered to each AHU through the shafts in the core by the primary air units (PAU), which are located at mechanical floors. The PAUs handle the outdoor air to 16.5 ℃ at machine dew points. All the fans in AHUs and PAUs are equipped with *VSD*s allowing more energy efficiency.

2.3 Design electricity loads of HVAC equipments

In the huge project, most HVAC equipments are also astonished. The design motor of the HV chiller are about 1300 *kW* with the dimension of length 6.4 *m*, width 3.2 *m* and height 3.4 *m*. The pumps associated with the water are equipped with motors with the power between 100 *kW* to 200 *kW*. Almost each AHU has the capacity of flow air rate 10 m^3/s with motor of 30 *kW*. Table 1 shows the summary of

Tab.1 Summary of design electricity loads of HVAC equipments(Standby units are excluded)

	Chiller	Pump	Cooling Tower Fan	PAU Fan	AHU Fan	Total
Number	6	36	11	29	152	234
Rated Power(kW)	1346			90		
Total load(kW)	8076	4374	990	513	4600	18533
Percentage	43.53%	23.58%	5.34%	2.77%	24.79%	

design power capacity of HVAC equipments involving chillers, cooling tower, pumps and fans of PAUs and AHUs. Chillers occupy 44 % of the total power load, the largest electricity consumer of the air-conditioning system. Pumps and AHU fans are the second largest consumers with about 24% and 25% portions respectively. The energy saving potential is mainly on the pumps, fans and fresh air flow rate.

3. IMPLEMENTATION ARCHITECTURE OF SYSTEM DIAGNOSIS AND CONTROL OPTIMIZERS

Figure 3 shows the implementation architecture of “Chiller Plant Control Optimizer” and the robust control strategies. All the DDC controllers of air systems are integrated into a LAN-based BMS. Supply air control optimizer is to optimize the temperature set point and static pressure set point with minimum energy consumption while keeping comfortable temperature and humidity environment as well as enough air circulation. The optimizer will be programmed in AHU local control stations because of not very complicated programming and demand on computation power. Fresh air control optimizer is to optimize the fresh air flow rate of each AHU. Optimal fresh air intake can guarantee acceptable IAQ with minimum energy consumption. The control optimizer will also be programmed in same local control station. The control/optimization logic and formulas will be provided by PolyU. The MVAC&BMS contractors implement the strategy in the programmable control stations with the support of PolyU.

The robust chiller sequencing control strategy and chiller plant optimizer include the supervisory control of chillers and pump as well as cooling towers. It is done by a complicated program with high demand on computation power. Therefore, a standalone control and optimization software package and a diagnosis package are developed running on a PC station interfaced with the main station of the chiller control system (BMS), as the control/ optimization and diagnosis need a great deal of the plant operation information. The standalone package will run in parallel with the chiller sequencing program provided by the MVAC&BMS contractors. The contractors provide the protocol or an interface for the communication between these packages and the main station of chiller control system. The control parameters of the optimizer mainly involves numbers of chiller, cooling tower, and pump to be operated, the set-point of supply chilled water temperature, the set-point of supply cooling water temperature, the set-point of water pressure differential of the worst water loop etc. When plant (chiller, cooling tower, pumps, etc.) sequencing is of concern, the chiller plant optimizer provided by PolyU will only provide the number of them to be operated and the chiller control system (ATC) will determine which one is used. A decision supervisor in the chiller control system is designed for the operators to set if the settings given by the “chiller plant control optimizer” are used or ignored (not used). The chiller performance monitoring and diagnosis strategy will be implemented in a standalone package probably running in the same PC station as the optimization package. This package will provide diagnosis information to management staff and will not feedback to chiller control.

4. ADDITIONAL METERING

The chiller control panel is connected to BMS. It mainly involves temperature measurements, water flow rate measurements and inlet guide vane control signal etc. This control signal can roughly indicate the status of load. Besides the measurement instruments of the original design, power meters involving current, voltage and power factor for each chiller are added to allow more efficient control. Pressure differential sensors are also added to monitor the pressure drops and flow rate change of the evaporators and condensers.

As a pilot project, the fresh air flow rate of only one office floor is monitored and controlled. The fresh air flow rate is controlled based on dynamic occupancy detection [Wang and Burnett 1999]. The CO_2 concentrations of return air, supply air, fresh air and critical zones are monitored. To decrease the effects of measurements of supply air flow rate on occupancy detection and fresh air control, air flow stations of high accuracy are added for supply air flow rate monitoring. Air flow meters are directly used for fresh air control. The powers of AHU fans and PAU fans are monitored with power meters.

Many BMS points for CO_2 sensor at this floor are reserved for future critical zone detection.

5. SYSTEM SIMULATION

EnergyPlus simulation program (a detail simulation model) is used to represent the building to produce the cooling load of each zone. The weather

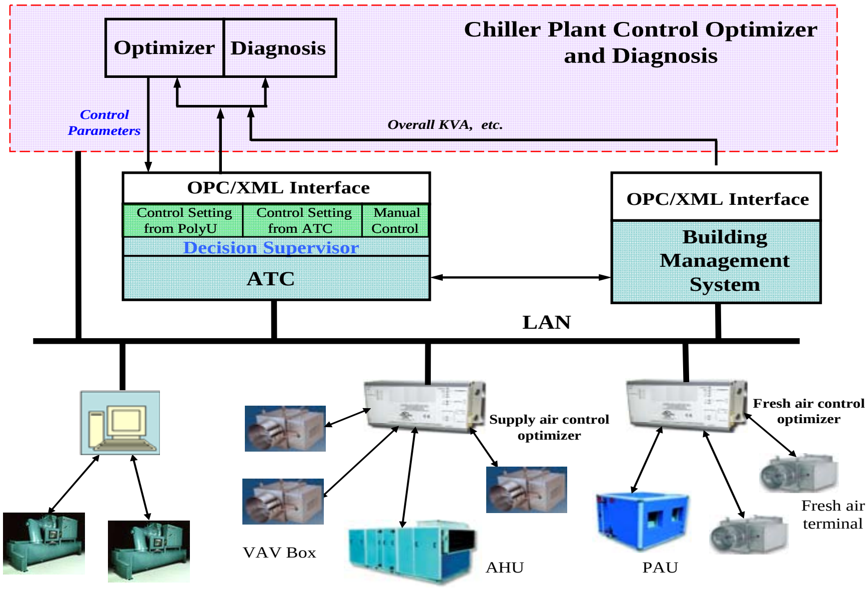

Fig. 3 Implementation architecture of strategies

data was the typical Meteorological Year type data of Hong Kong (1989). The building was simulated for one year (8760 hours). The necessary inputs for EnergyPlus simulation to represent the real building were detailed descriptions of building envelopes, floors and ceiling, design peak occupancy, lighting power and equipment power, and their corresponding pattern profiles for weekdays and weekend days etc. The furniture and carpets could not be described in detail. They were simplified as specific wood plate and specific carpet plate with certain areas respectively.

Chiller simulation [12] is to simulate the chiller performance dynamically under various working conditions. The simulation involves compressor, condenser/evaporator, motor power consumption and thermal capacitances of components associated with heat transfer in the chiller. Cooling tower simulation is developed to simulate the states of outlet air and outlet water of the cooling tower, which is based on steady-state energy and mass balance on an incremental volume. The effectiveness of cooling tower is used to simulate the heat and mass transfer processes in the cooling tower.

The variable-speed pump set is simulated by a steady-state pump, a steady-state frequency inverter and a dynamic actuator of the inverter. The frequency at the outlet of the inverter is linear to the input signal from actuator. The efficiency of the inverter is included within the model of pump energy performance. The energy performance and pump characteristics at various speeds are simulated using fourth-order polynomial functions. The coefficients are determined by regression using the performance data from manufacturer's catalogue. The pressure losses across pipes, components such as cooling coils, gate valves, and control valves are represented as the coefficient of resistance times the dynamic pressure.

AHU simulation is mainly to simulate the energy performance, outlet water states and outlet air states. The simulation involves dynamic fan model, duct model and cooling coil model etc. [15].

6. SIMULATION RESULTS

6.1 Benchmark electricity consumption

The benchmark of electricity consumption of HVAC equipments is estimated based on the "measurements" of instruments provided by the drawings from the consulting company as well as the control strategies described in the drawings. The control of benchmark reference works properly but without using the " additional metering systems". The main control strategies based on original design mainly involve chiller sequencing control, cooling tower sequencing control, secondary-pump variable frequency control, AHU fan variable frequency control, fresh air control. Chiller and cooling tower controls are conventionally sequencing controls. The supply chilled water temperature is fixed at 5.5 ℃. The variable frequency control of secondary pump is based on the fixed water pressure differential set-point of the water loop. AHU fan control is based on fixed static pressure set-point. The fresh air control rate is constant for all the office floors and the block building.

6.2 Optimal electricity consumption

The optimal electricity consumption is estimated based on the control strategies of PolyU. It is assumed that the "additional" metering system allows more efficient control. The metering system involves water side measurements and the air-side measurements of only one typical floor. The control strategies also mainly involves chiller sequencing control, cooling tower sequencing control, secondary-pump operation number and variable frequency control, AHU fan variable frequency control, fresh air control. The fresh air flow rate set-point is reset based on the dynamically detected occupancy. The static pressure set-point of AHU VAV system is also reset to make the dampers of VAV boxes at the positions as fully open as possible while maintaining the indoor thermal requirements. The water pressure differential set point is also reset to make the control valve at the position as fully open as possible to reduce the water pressure loss leading to the pump energy saving. All the cooling towers are designed with two speeds (i.e., high speed and low speed). The optimal operation mode is based on the principle of privileged low speed because of obvious energy saving at low speed. The high speed is put into operation gradually when the cooling capacity of all the towers with low speed cannot satisfy the requirements.

Tab.2 Summary of energy consumption and savings

Energy Consumption	Conventional	Percentage	Optimal	Percentage	Saving	Saving(%)
Chiller(kWh)	24994313	50.57	24567965	52.52	426348	1.71
Cooling Tower(kWh)	3725820	7.54	3502270	7.49	223550	6.00
Pump(kWh)	10601505	21.45	9270556	19.82	1330949	12.55
AHU Fan(kWh)	8278738	16.75	7609280	16.27	669458	8.09
PAU Fan(kWh)	1823957	3.69	1823957	3.90	0	0.00
Fresh air(MJ) (One Floor)	247454		185215		62239	25.15
Fresh air(kWh)(One Floor)					6915	
Total(kWh)	49424333		46774027		2657221	5.38

For chiller system, the chiller operates at different energy efficiency (different COP values) according to the working conditions such as inlet cooling water temperature, outlet chilled water temperature etc. Normally, the chiller operates with the highest COP at about 80% of the maximum cooling capacity. One more chiller in operation may lead to less electricity consumption because of operating at high COP values. However, one more chiller in operation means more pump energy consumption. High outlet chilled water temperature is preferable for chiller electricity saving while high outlet chilled water temperature deteriorates the heat exchange efficiency. Therefore, more pump energy is consumed to delivery more chilled water for cooling coils to compensate the inverse effects of high chilled water temperature. Therefore, a global control strategy is used to determine the number of chillers in operation, the set points of the outlet chilled water temperature and the inlet condensing water to minimize the energy consumption of the whole cooling and chilling systems while satisfying the thermal requirement for the whole system.

6.3 Money saving through electricity peak demand control

In Hong Kong, Time of Use (TOU) Rate has been implemented since 2001 to encourage people to reduce their electricity consumption during the peak-load period and/or to shift their load to off-peak period either by a change in consumption behavior or by an adoption of load shifting technologies. This concept is to lower annual energy costs while without reducing the overall amount of electricity used by reducing the electricity use during peak periods. This measure is very attractive to large commercial electricity consumers. In this study, a hybrid building model is developed to predict the total cooling requirement on-line. A robust strategy is developed to operate the air-conditioning system in advance to cooling down the building while reducing the electricity use during peak periods mostly in the morning by monitoring the electricity consumption of the whole building on-line. The reduced electricity use can lead to the total electricity charge savings.

6.4 Results analysis and payback period

The benchmark electricity consumption and optimal electricity consumption for the typical meteorological year are summarized in Table 2. The total benchmark electricity consumption for one year is about 49 *million kWh*. Chillers occupy about 50 % of the total electricity consumption. The second is electricity consumption of pumps, about 21 %. The third one is the electricity consumption of AHU fans, about 17 %. The optimal electricity consumption of HVAC systems is estimated as 46.9 *million kWh*. It involves the optimal static pressure set points for all the AHU fans. When the fresh air is controlled based on dynamic occupancy detection, it can save 62239 *MJ* cooling load for one year of each floor. The saved cooling load is equivalent to 6915 *kWh* (Considering global COP=2.5). By comparing to the benchmark electricity consumption, the total electricity saving using our control strategies is about 2.66 *million* about 5.4 % saving.

The operation saving of the above HVAC systems is equivalent to 2,338,354 *HK$* with the electricity price 0.88 *HK$/kWh* published by the main power companies in Hong Kong. The cost on the additional water-side and air-side metering systems as well as relative items such as hardware, software programming etc. is about 2.32 *million HK$*. Therefore, the payback period is about only one year. It is quite preferable.

7. SUMMARY

This paper presents the initial work of a research project “Energy efficiency through intelligent control and diagnosis” for International Commerce Center, the highest building in construction in Hong Kong. The initial work is mainly the control strategy development, performance evaluation and economic analysis. A number of alternative control strategies are proposed to improve the energy efficiency of the building with additional metering systems expect the current measurement of the original design. The building cooling load is simulated using EnergyPlus based on the original design information provided by the consulting company and developer, such as the physical properties of building envelopes and floor slab, load of occupancy, lighting and equipments etc. The electricity consumption of HVAC system is simulated using self-developed simulation packages. The benchmark electricity consumption is estimated based on the control strategies and the “measurements” of instruments provided in the original design. The consumption is about 49.4 million kWh. The optimal electricity consumption of HVAC equipments is estimated about 46.8 million kWh, which is based on the proposed alternative control strategies while the “additional” metering system allows more efficient control. The cost on the additional metering systems as well as relative items such as hardware, software programming etc. is about 2.32 million HK$. Therefore, the payback period is preferable about only one year. Phase I of the building will be put in operation at the end of next year. The detail performance evaluation and operation commissioning will be reported subsequently in the preceding meetings with the completion of the building and HVAC systems.

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